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Digital aperture correction

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DIGITAL APERTURE CORRECTION

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Summary

An experimental digital aperture corrector has been constructed which provides vertical correction together with 'in-band' horizontal and 'out of band' horizontal aperture correction of the luminance component of 8-bit p.c.m. Red, Green and Blue signals from an experimental digital signal processing channel. The vertical and horizontal aperture correctors operate in parallel on a 'luminance' signal matrixed from R, G, B inputs to produce a '7 point' correction signal which is added to the R, G, B inputs, suitably delayed to give 8-bit corrected R, G, B outputs.

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DIGITAL APERTURE CORRECTION

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DIGITAL APERTURE CORRECTION

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1. Introduction

Aperture correctors are required in picture sources to compensate for high frequency losses due to:—

(a) Lens imperfections

(b) Image spreading in a camera tube target or film emulsion

(c) Scanning spot size in a camera tube or telecine flying-spot tube

(d) Display spot size.

These effects all spread the image (of each spot of light in the original scene) over a finite area or aperture, thus softening the displayed picture. Aperture correctors attempt to reduce the effects of this spread by subtracting from the signal a proportion of the signals from neighbouring picture elements.

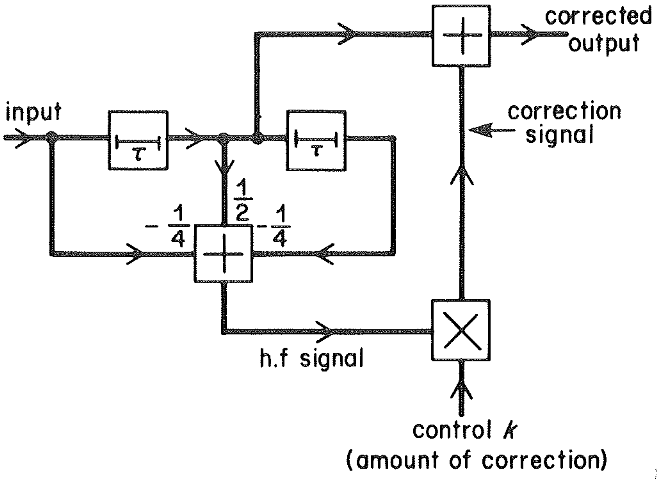

Fig. 1 - Simple aperture corrector — Block diagram

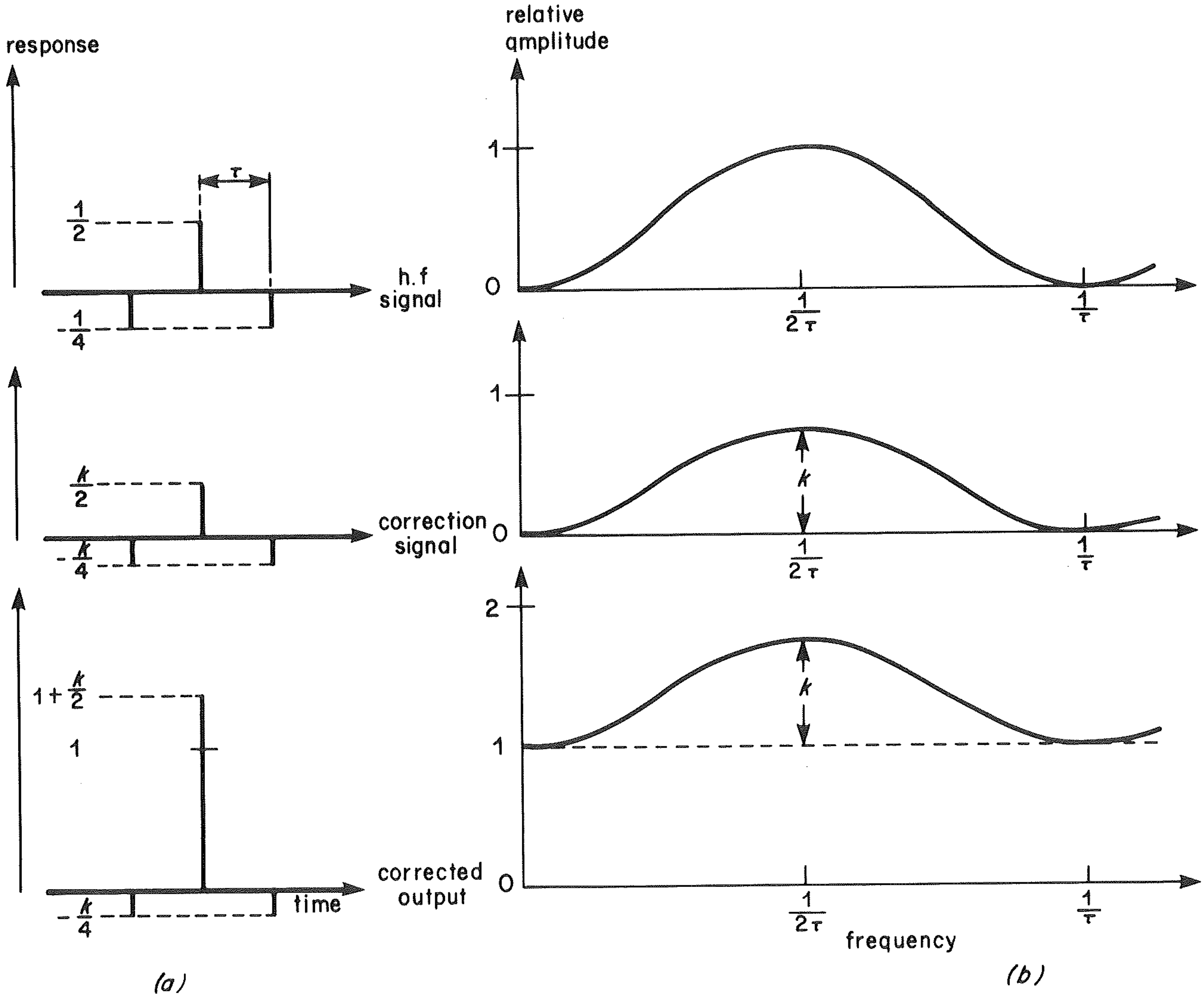

Fig. 2 - Simple aperture corrector — Responses
(*a*) Impulse responses (*b*) Amplitude/frequency characteristics

Line delays are required to obtain signals from the lines above and below the point of interest but analogue delays are prone to noise, spurious reflections and high frequency loss. Digital delays are, however, inherently loss and reflection free, and noise can be reduced to any required level by coding the signal with sufficient resolution (i.e. using enough bits). A digital aperture corrector therefore offers improved signal quality as well as the other advantages of digital systems such as improved accuracy, stability and reliability. More sophisticated correction is also more practicable.

The digital aperture corrector described in this report forms part of an experimental digital processing channel.[1] This supplies the corrector with gamma-corrected Red, Green and Blue signals, each sampled at approximately 13·3 MHz with 8 bits per sample. (The present high cost of analogue-to-digital conversion would make the digital aperture corrector too expensive to be used on its own in an otherwise analogue system.)

The digital corrector is in many ways similar to existing analogue correctors, as discussed in Sections 2, 3 and 4 which deal with the principles of monochrome aperture correction. The experimental digital corrector does, however, handle colour signals slightly differently, as described in Section 5. The details of the digital hardware are given in Section 6.

2. Horizontal aperture correction

Fig. 1 shows a simple aperture corrector. This corrects for high frequency loss by adding a high frequency correction signal derived from the original signal by a symmetrical transversal (tapped delay line) filter.

Fig. 2 shows how this corrector gives a frequency response which rises from unity at zero frequency to a maximum at ($\frac{1}{2}\tau$). The height of the peak in the corrected output is determined by the amount (k) of correction signal added. The frequency of the peak is determined by choosing the delay line length (τ) and may be adjusted to match the kind of loss being corrected.

Most aperture losses are approximately gaussian (or 'normally' distributed). As an example, Fig. 3 shows the amplitude/frequency characteristics of a typical system with a (σ = 53 ns*) gaussian loss, corrected by correctors with various values of τ. In each case the amount of correction (k) has been chosen to give unity gain (i.e. perfect correction) at low frequencies. This is known as the maximally flat condition. (In practice, low frequencies would probably be over-corrected to offset the shortcomings at high frequencies and thus improve the subjective sharpness. However, since over-correction produces low frequency ringing it is best to design aperture correctors to give a good maximally flat response so that less over-correction is required.)

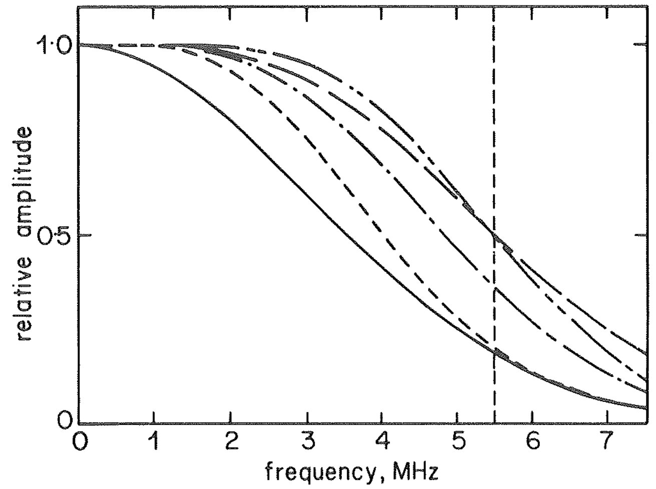

Fig. 3 - Aperture corrected gaussian frequency characteristics (σ = 53 ns)

——— (a) No correction – – – – (b) τ = 150 ns; k = 0·25
—·— (c) τ = 75 ns; k = 1 —— —— (d) τ = 7·5 ns; k = 100
—··— (e) Second order τ = 75 ns; k_1 = $^{11}/6$; k_2 = $^{-5}/24$

Gaussian aperture losses are most accurately corrected by a corrector with τ very small and k very large, Fig. 3(d). This puts the peak correction at a very high frequency so that the correction rises at an ever increasing rate from d.c. to beyond the edge of the video band.

Figs. 4 and 5 show that correctors with short delays also give the best impulse and step responses.

Digital aperture correctors must operate on sampled signals and, as a result, the minimum delay which can be

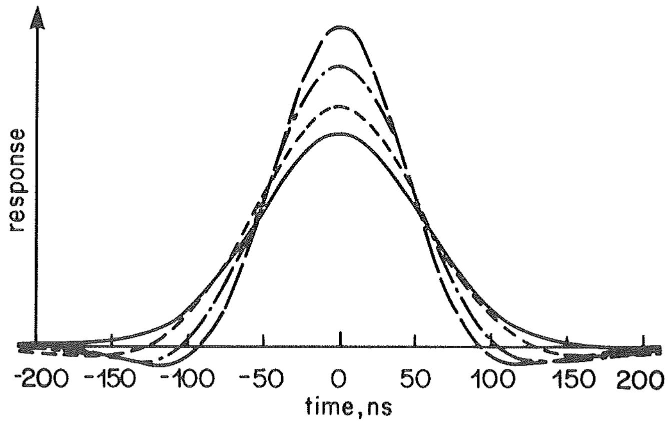

Fig. 4 - Aperture corrected gaussian impulse responses (σ = 53 ns)

——— (a) No correction – – – (b) τ = 150 ns; k = 0·25
—·—— (c) τ = 75 ns; k = 1 —— —— (d) τ = 7·5 ns; k = 100

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* σ is the standard deviation (amount of spread) of a gaussian system whose impulse and frequency responses are respectively:

$$f(t) = (\sigma\sqrt{2\pi})^{-1}\exp(-t^2/2\sigma^2)$$

$$F(\omega) = \exp(-\omega^2 . \sigma^2/2)$$

Maximally flat correction is obtained if $k = 2\sigma^2/\tau^2$.

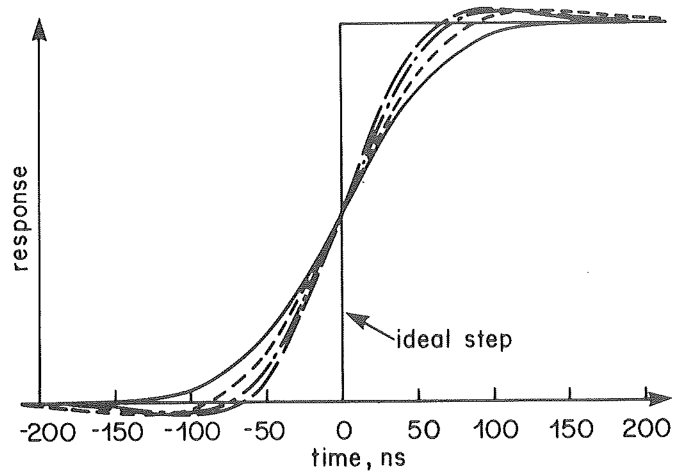


Fig. 5 - Aperture corrected gaussian step responses ($\sigma = 53$ ns)

(*a*) No correction
(*b*) $\tau = 150$ ns; $k = 0{\cdot}25$
(*c*) $\tau = 75$ ns; $k = 1$
(*d*) $\tau = 7{\cdot}5$ ns; $k = 100$

employed in aperture correction is restricted to one sampling interval. In the case of sampling at 13·3 MHz the sampling interval is 75 ns. This limits the performance of first order digital correctors to that shown in curves (*b*) or (*c*). However, an improved performance can be obtained by using the second order corrector shown in Fig. 6. This gives a better response within the video band than any of the first order correctors (Fig. 3(*e*)). Fig. 7 shows that if k_2 in Fig. 6 is negative, this corrector subtracts 'in band' correction to prevent over-correction of low frequencies and allows a relatively large amount of 'out of band' correction to be applied while maintaining a maximally flat response.

3. Vertical aperture correction

The arrangement shown in Fig. 1 may alternatively correct losses of vertical resolution (due to vertical image spread). In this case the delay elements (τ) become line delays (64 μs) so that the adder/subtractor combines signals from three picture points vertically above one another, to produce a vertical detail signal. A controlled amount of this is added to the (suitably delayed) input signal to give a corrected output (i.e. with increased vertical detail).

The three picture points used are all from the same field and are therefore spaced by 2/625ths of a picture height (equivalent to 135 ns horizontally). This gives the vertical detail signal a maximum response at 156¼ cycles per picture height (equivalent to 3·7 MHz horizontally) which is considerably 'in band' (i.e. it is unable to correct the highest possible vertical frequencies in the region of 312½ cycles per picture height ($\simeq$ 7·4 MHz)). It would be possible to correct these frequencies by using a field store to give access to the lines of the other field, which are closer. This would not only be expensive but would also affect movement portrayal, and accentuate the 25 Hz flicker caused by interlaced scanning.

Second order vertical correction would only affect relatively low spatial frequencies and cannot overcome the basic limitations of 'in band' correction mentioned above. It was not therefore used in the digital corrector.

Delays exactly 1 line (64 μs) long are only possible in a digital system if the sampling frequency is a harmonic of the line frequency. Otherwise using the nearest whole number of sampling periods may give delays which are up to ±37·5 ns in error (if the sampling frequency is approximately 13·3 MHz). As a result, the three signals used by the vertical aperture corrector may be taken from picture

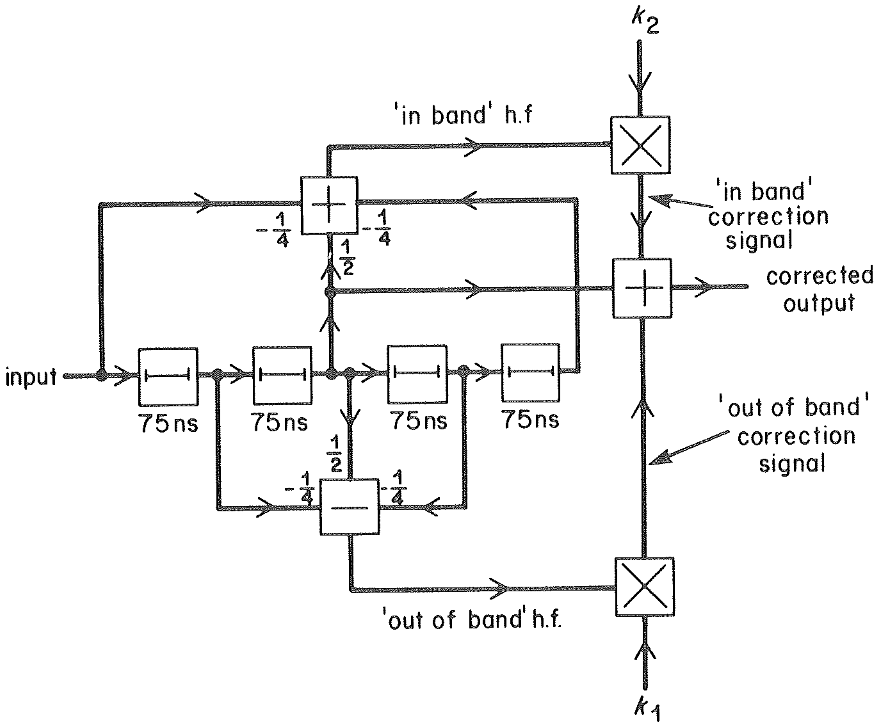
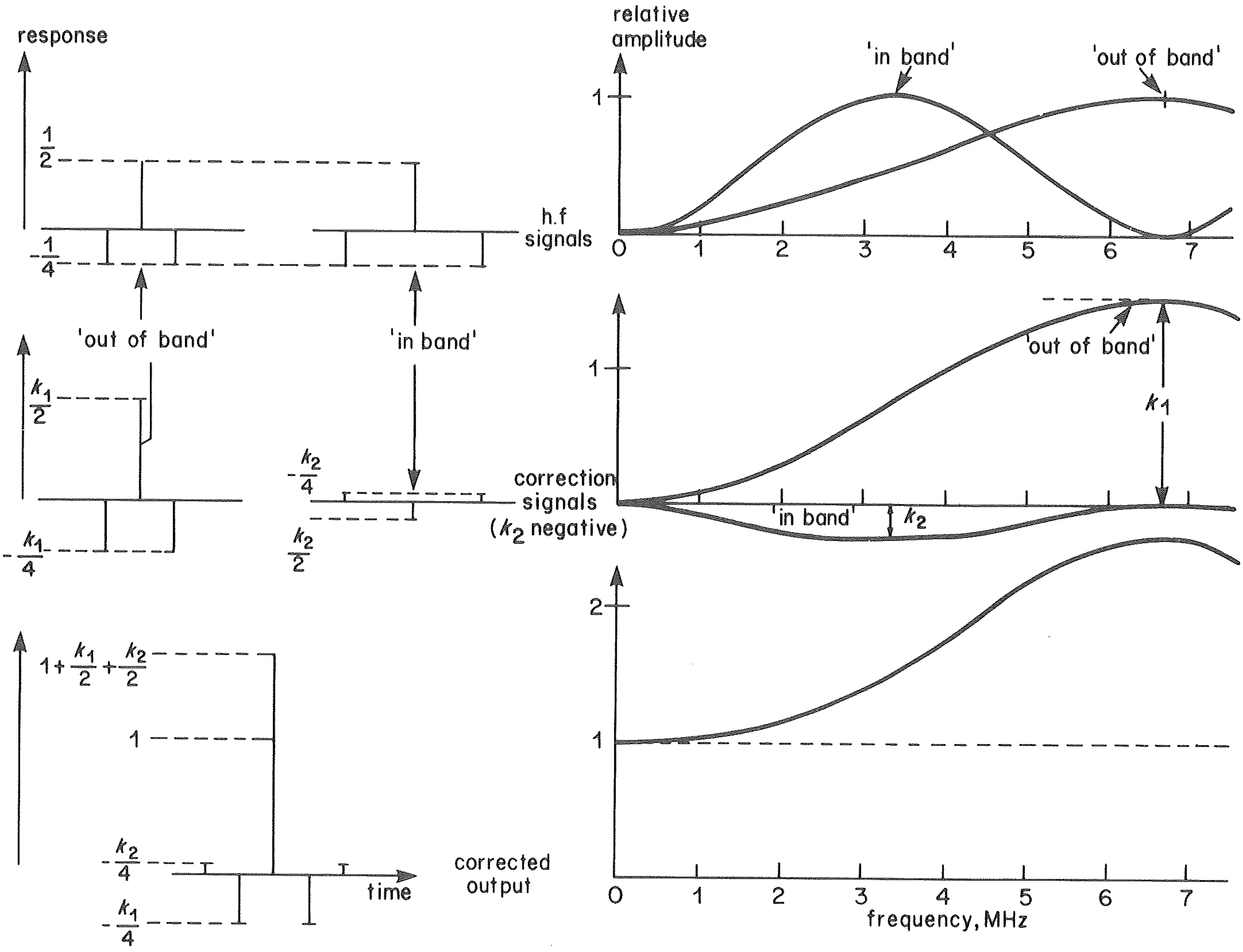


Fig. 6 - Second order aperture corrector – Block diagram



(*a*) (*b*)

Fig. 7 - Second order aperture corrector — Responses

(*a*) Impulse responses (*b*) Amplitude/frequency characteristics

points which are not vertically aligned but slope at up to ±16° from the vertical. Instead of giving maximum correction of vertical detail and ignoring horizontal detail the 'vertical' aperture corrector therefore gives maximum and minimum corrections on patterns which slope at up to ±16° from the true vertical and horizontal. For example, one commonly used clock frequency is three times PAL colour subcarrier frequency ($3f_{sc}$); the nearest delay to 1 line is 851 clock periods which is 19 ns less than 1 line; giving a slope of ~8°.

This effect is very slight and although it can be demonstrated by displaying the vertical correction signal on its own, it is imperceptible on the final corrected picture.

4. Two-dimensional aperture correctors

There are two ways of combining vertical and horizontal aperture correction to give correction in both directions:

(a) Cascaded (multiplicative) horizontal and vertical correctors.

Some analogue aperture correctors use this system where the two correctors are merely placed in tandem (the output of one being the input of the next). This is also called 9 point correction, since, with the first order horizontal and vertical correctors, the corrected output is a combination of signals from 9 picture points multiplied by the coefficients:

$\frac{k_h}{4}\cdot\frac{k_v}{4}$	$-\left(1+\frac{k_h}{2}\right)\cdot\frac{k_v}{4}$	$\frac{k_h}{4}\cdot\frac{k_v}{4}$
$-\frac{k_h}{4}\left(1+\frac{k_v}{2}\right)$	$\left(1+\frac{k_h}{2}\right)\left(1+\frac{k_v}{2}\right)$	$-\frac{k_h}{4}\left(1+\frac{k_v}{2}\right)$
$\frac{k_h}{4}\cdot\frac{k_v}{4}$	$-\left(1+\frac{k_h}{2}\right)\cdot\frac{k_v}{4}$	$\frac{k_h}{4}\cdot\frac{k_v}{4}$

(where k_h is the amount of horizontal correction and k_v is the amount of vertical correction.)

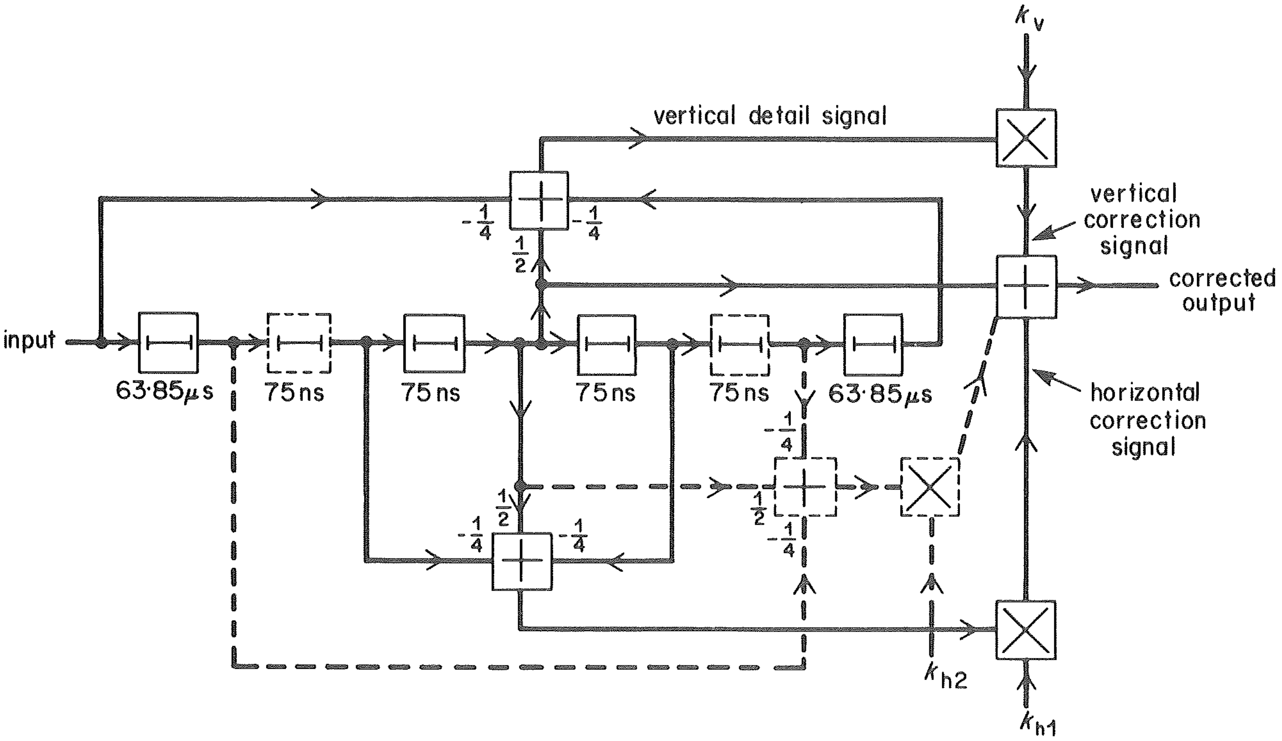


Fig. 8 - Parallel 2-D aperture corrector — block diagram

(b) Parallel (additive) horizontal and vertical correction

The analogue telecine aperture correctors now used in the BBC, and the experimental digital corrector generate horizontal and vertical correction signals simultaneously and add them both to the (suitably delayed) input signal. This arrangement is shown in Fig. 8 which also shows (dotted) the second-order horizontal correction used in the experimental digital system. This parallel arrangement minimises the total signal delay and prevents rounding errors, generated in the first corrector, being re-rounded in the other.

The corrected output is a combination of signals from 5 picture points multiplied by the coefficients:

	$-\frac{k_v}{4}$	
$-\frac{k_h}{4}$	$\left(1+\frac{k_h}{2}+\frac{k_v}{2}\right)$	$-\frac{k_h}{4}$
	$-\frac{k_v}{4}$	

5 point and 9 point corrections give the same result with signals consisting only of horizontal frequencies (e.g. Test Card F resolution bars) or vertical frequencies (e.g. Venetian blinds). But they respond differently to diagonal patterns which contain both horizontal and vertical frequency components. There has in the past been some discussion about which system gives the best overall correction.

To resolve this argument a computer was used to plot the 2-dimensional (2-D) frequency responses of systems with gaussian aperture loss and various forms of 2-D aperture correction. The results are shown in Figs. 9(*a*) — (*e*). These figures represent system response in two dimensions by attenuation contours 1 dB apart.

Fig. 9(*a*) shows an uncorrected (53 ns) gaussian loss. Figs. 9(*b*) and (*c*) have been corrected by 5 point and 9 point corrections respectively to give maximally flat correction at low frequencies. There is very little difference between the two. Their responses to pure horizontals and pure verticals are identical and the diagonal responses differ by no more than 1 dB. The 9 point corrector gives a slightly better response on diagonals but in practice this may be a disadvantage, since there is more danger of overcorrecting diagonals. This is illustrated by Figs. 9(*d*) and (*e*) which have each been overcorrected, as they would normally be in practice. Again the responses of the two systems are identical along vertical and horizontal axes. The 9 point corrector gives far more overcorrection of diagonals and there is therefore more danger of ringing on diagonal patterns. So for practical aperture correctors (which are likely to be operated with slight amounts of overcorrection) the 5 point correction is to be preferred since it gives a more isotropic response.

The experimental digital corrector is similar to a 5 point corrector but includes second order horizontal correction (as shown dotted in Fig. 8). This gives an overall 7 point correction aperture.

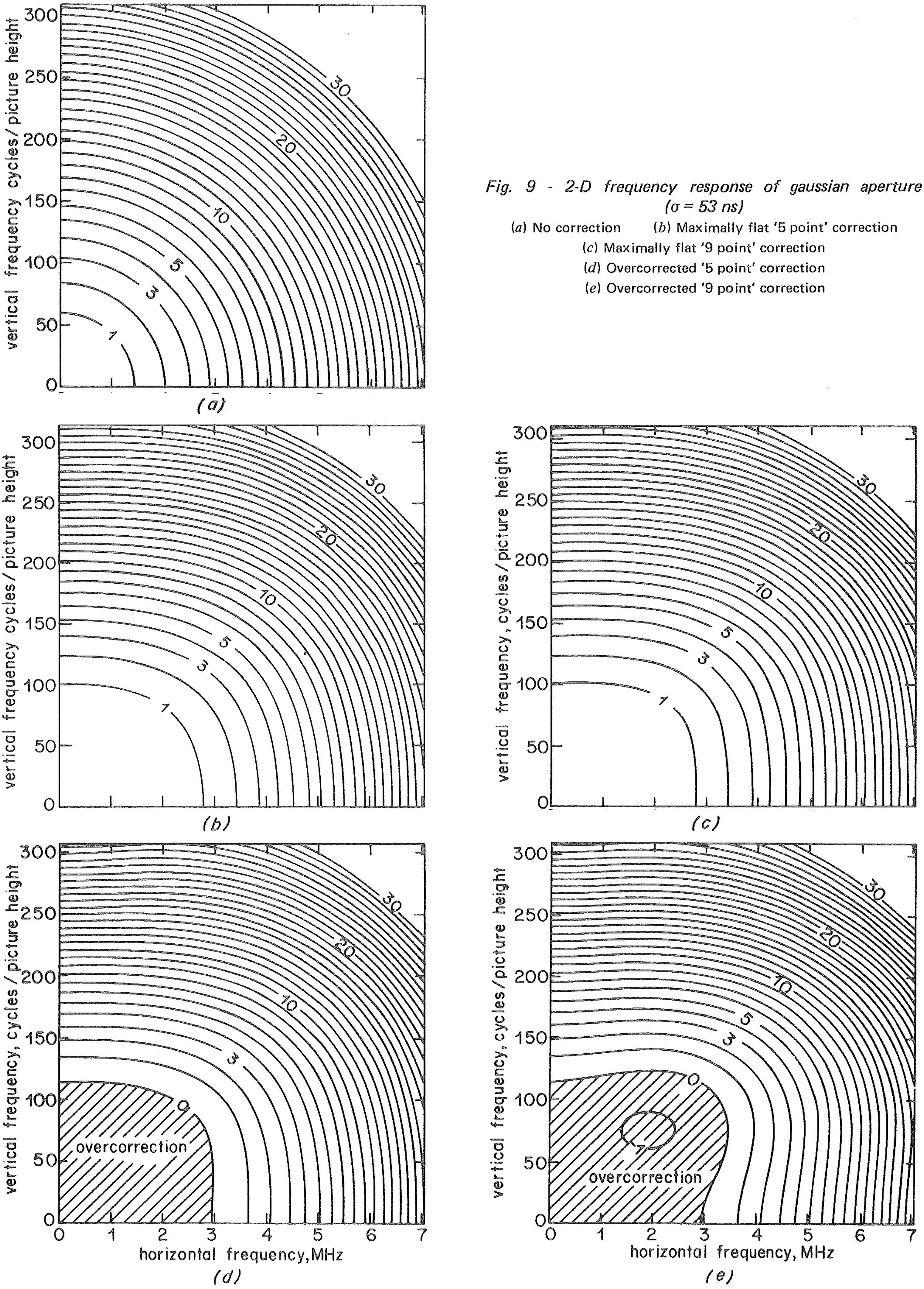


Fig. 9 - 2-D frequency response of gaussian aperture (σ = 53 ns)

(*a*) No correction (*b*) Maximally flat '5 point' correction

(*c*) Maximally flat '9 point' correction

(*d*) Overcorrected '5 point' correction

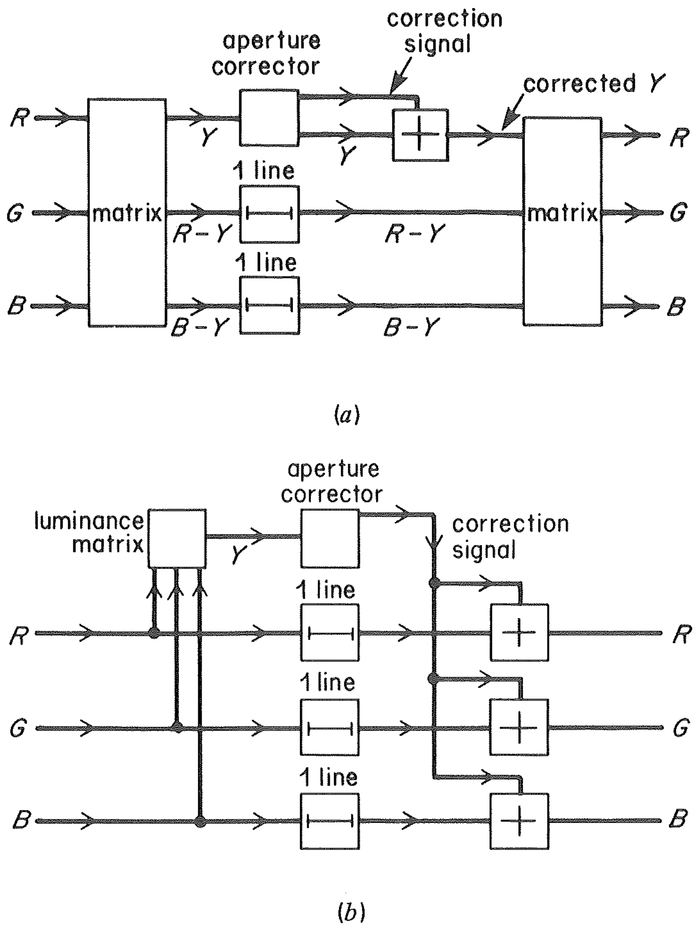
(*e*) Overcorrected '9 point' correction

5. Colour

It would be possible to correct the Red, Green and Blue signals using three separate aperture correctors. In practice only the luminance component needs correcting and it is therefore possible to save triplicating the corrector.

The correction of the luminance signal takes at least one line and it is therefore necessary to delay the chrominance components to match. Some colour cameras achieve this by deliberately misregistering the colouring tubes. This is not possible in flying spot film scanners and their correctors usually delay R-Y and B-Y signals, recombining them with the corrected Y to give corrected R, G and B, as shown in Fig. 10(*a*). Digital formation of R-Y and B-Y and recombination with Y to form corrected R, G and B would be extremely complicated and expensive, as it would involve a large number of multiplications by coefficients. Fortunately it is not necessary.

Instead, the digital corrector delays all three colour separation signals (R, G and B) and adds a (delayed) correction signal to all three signals to give corrected R, G and B, as shown in Fig. 10(*b*). The correction signal is obtained from a luminance signal matrixed from the input R, G, B. The matrix coefficients need not be very exact and for simplicity $Y = \frac{1}{4}R + \frac{5}{8}G + \frac{1}{8}B$ has been chosen.



(*a*)

(*b*)

Fig. 10 - Aperture correction at colour signals — block diagrams

(*a*) Existing analogue corrector (*b*) Experimental digital corrector

6. Digital hardware

The digitally instrumented corrector generates a 7 point aperture correction signal from a luminance signal matrixed from the incoming R,G,B and adds this correction signal to each of the delayed R,G,B signals. Fig. 11 shows the system in detail.

The system operates in a parallel-bit mode with a $\sim$13·3 MHz sampling frequency throughout. Most of the system employs 8 bits per sample, but extra bits generated by arithmetic operations are preserved in some places.

Quad D-type flip-flops (type 74175) are used for picture-element (75 ns) delays and to re-time the data after arithmetic operations. The line delays use quad 256-element MOS shift registers (type 1402) to provide 777 picture-elements of 8 bit storage. This is sufficient to delay the active lines by 777 clock periods. The total delay is made up to approximately one line period (i.e. 851 clock periods) by stopping the clock pulses during the line blanking period. By freezing propagation through the line delays for different lengths of time the exact delays can be adjusted to allow for processing delays. The total delay from R,G,B input to corrected R,G,B output is one line plus 20 clock pulses. Apart from the line delays the system uses ordinary TTL throughout.

The three correction signals corresponding to (a) vertical, (b) 'out of band' horizontal and (c) 'in band' horizontal corrections are controlled and added together by a 'three product summer' capable of multiplying each of three 12-bit numbers by a 6 bit coefficient and adding the answers. The available coefficients are: k_v (0 to 8 in steps of $^1/8$th); k_{h_1} (0 to 8 in steps of $^1/8$th); and k_{h_2} (–4 to 4 in steps of $^1/8$th). The three product summer can only handle positive inputs so the correction signals are represented in offset binary. The weighted offsets are subtracted from the weighted correction signal output before it is added to the delayed R,G,B signals.

The correction adders also provide clipping and blanking.

7. Conclusions

An experimental digital aperture corrector has been constructed which gives conventional vertical correction and 'second order' horizontal correction of the luminance component of 8-bit p.c.m. Red, Green and Blue digital signals. Second order horizontal aperture correction, with separate control of 'in band' and 'out of band' corrections, allows more accurate correction of gaussian aperture loss.

The vertical and horizontal correction signals are generated in parallel and added together since this gives a more isotropic two-dimensional response than cascaded horizontal and vertical correctors.

The combined luminance correction signal is added to delayed Red, Green and Blue inputs to produce the corrected Red, Green and Blue outputs. The alternative

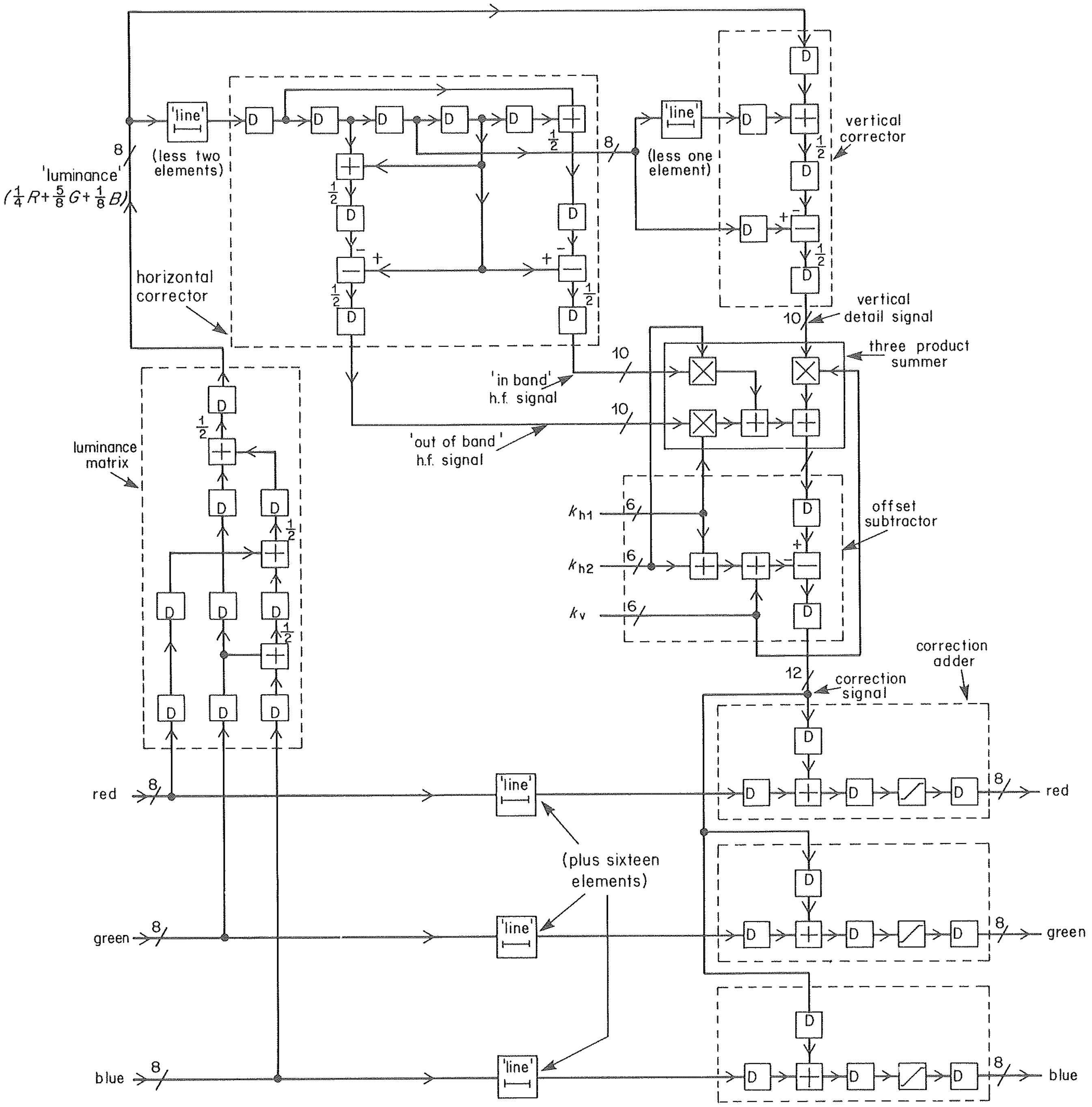


Fig. 11 - Experimental digital aperture corrector

method often used in analogue correction of matrixing a corrected luminance signal with delayed R-Y and B-Y would be unnecessarily complicated if performed digitally.

The digital aperture corrector offers the required performance together with instrumental advantages over its analogue counterpart, particularly with regard to accuracy, stability, noise, and other signal distortions.

8. References

1. OLIPHANT, A. 1978. A digital telecine processing channel. BBC Research Department Report in course of preparation.

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